233

DESIGN PEAK DISCHARGE FOR SMALL WATERSHEDS IN INDIANA

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by

I. P. WU

and

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Joint Highway Research Project

PURDUE UNIVERSITY
LAFAYETTE INDIANA

Technical Paper

DESIGN PEAK DISCHARGE FOR SMALL WATERSHEDS IN INDIANA

TO: K. B. Woods, Director
Joint Highway Research Project

March 20, 1963

FROM: H. L. Michael, Associate Director
Joint Highway Research Project

File: 9-8-1
Project: C-36-62A

One of the research projects which has been active in the Hydraulics Laboratory at Purdue and which has been financed by the Project is a study of the runoff from small watersheds. Mr. I. P. Wu a Graduate Assistant on our staff has been working on this study and in 1961 presented a report of the research to that date. During 1961-62 Mr. Wu was employed by the Indiana Flood Control and Water Resources Commission and continued work there in related areas. Mr. Wu has now returned to Purdue and is continuing the research on small watersheds.

From the work to date, two proposed technical papers have been prepared. One of these co-authored by Dr. J. W. Delleur, under whose direction Mr. Wu has been working, is attached. It is a summary of the research completed at the Project and will be submitted to ASCE for possible publication. The other paper summarizes the work and activity of Mr. Wu while with the Indiana Flood Control and Water Resources Commission and is being sponsored by that organization. Copies will be available at a later date.

The paper "Design Peak Discharge for Small Watersheds in Indiana" by I. P. Wu and J. W. Delleur is presented for approval of publication.

Respectfully submitted,

Harold L. Michael, Secretary

HLM:kmc

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by
I. P. Wu
Research Assistant
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Associate Professor

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Purdue University
Lafayette, Indiana

March 20, 1963

DESIGN PEAK DISCHARGE

FOR

SMALL WATERSHEDS IN INDIANA

by

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ABSTRACT

A study is made of the hydrology of watersheds less than 200 square miles in area located in the State of Indiana for which flows are recorded by the U.S.G.S. A statistical frequency analysis of the peak flows was made by means of Gumbel's extreme value theory. A geomorphological study, involving the quantitative determination of five watershed characteristics, combined with the use of multiple correlation techniques serves to establish a formula for estimating the peak discharge of ungaged watersheds in Indiana.

SYNOPSIS

The purpose of this research is to study the hydrology of watersheds less than 200 square miles in area throughout the State of Indiana and to establish methods of estimating the peak discharge from these watersheds. The study will include four parts: a statistical analysis of existing data, a geomorphological study of selected watersheds, a study of small watershed storm hydrographs, and an analysis of overland flow. The present paper summarizes the work done on the first two parts.

The statistical analysis has been made by means of the extreme value method. The 25-year instantaneous peak flow has been determined for all the gaging stations with a drainage area of less than 200 square miles for which the U.S.G.S. publishes records. For those watersheds for which sufficient topographic data were available, five geomorphological parameters were calculated: the watershed area, the mean relief, the main stream slope, the stream density, and the watershed shape factor. A multiple correlation was made between these variables and the 25-year instantaneous peak flow. A correlation chart is given to obtain graphically the peak flow for small watersheds from these five geomorphological parameters. A simple formula containing only three geomorphological parameters was introduced as a first approximation of flood peak discharge determination. An expression is given to calculate the peak discharge for any frequency from the 25-year peak discharge. Similar analyses could be done for other regions.

INTRODUCTION

The determination of the required waterway area of a bridge or the selection of the size of a culvert are problems which require an accurate estimate of the peak flood discharge that will pass through the structure. The determination of this discharge is more difficult for small watersheds because the majority of them are ungaged. There are very few gaged small watersheds on which to base an estimate. Particularly in the state of Indiana, there is very little information on watersheds less than 200 square miles. There are only twelve watersheds of less than 100 square miles, and seventeen watersheds with an area between 100 and 200 square miles for which the U.S.G.S. is currently reporting flows. A research program was initiated at Purdue University to obtain reliable methods for estimating the peak discharge for a safe and economic design of highway drainage structures, serving watersheds in Indiana of less than 200 square miles but larger than 20 square miles.

The existing methods are empirical and fail to take into account the factors upon which the runoff depends. Kinnison (3) in 1946 and Chow (4) in 1962 have given a complete list of empirical formulas which include

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3 Kinnison, H. B., "Flood-Flow Formulas," Jour. Boston Soc. Civil Engr., V. 33, pp. 1-19, January, 1946.

4 Chow, V. T., "Hydrologic Determination of Waterway Area for the Design of Drainage Structures in Small Drainage Basins," Engineering Experiment Station Bulletin No. 462, University of Illinois, 1962.

the watershed characteristics. The most frequently used formulas are those of Talbot[5] published in 1887 and Meyer[6] in 1879 and the Rational formula originally derived by Mulvany[7] in 1857. Talbot's formula was originally intended for locations in Illinois. It estimates the waterway area from the watershed area. The formula is:

$$A = CM^{3/4} \qquad (1)$$

where A is the required waterway area in square feet, M is the watershed area in acres, and C is a coefficient varying between 1/5 and 1 depending on the slope and character of the watershed. The selection of the coefficient depends, among other things, on the experience of the designer. Due to the various factors that affect the runoff other than the watershed area, the value of the coefficient C cannot be accurately determined to represent all the watershed characteristics. Talbot's formula is unsatisfactory for a safe design of a hydraulic structure.

Yule[8] in 1950 developed a similar formula for locations in Indiana. The required waterway area is expressed as a function of the 2/3 power of the

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5 Talbot, A. N., "The Determination of Waterway for Bridges and Culverts," Selected Papers of the Civil Engineer's Club, Technograph No.2, University of Illinois, 1887-8, pp. 14-22.

6 Meyer The formula was first published in a paper read by Cleemann before the Engineers' Club of Philadelphia in 1879.
Cleemann, T. M., "Railroad Engineers' Practice, Discussion of Formulas," Proceedings, Engineers Club of Philadelphia, V. 1, pp. 146, 1879.

7 Mulvany, T. J., "On the Use of Self Registering Rain and Flood Gauges in Making Observations of the Relations of Rainfall and of Flood Discharges in a Given Catchment," Transactions of the Institution of Civil Engineers of Ireland, V. 4, Part II, pp. 18, 1857.

8 Yule, B. B., "Bridge Waterway-Area Formula Developed for Indiana," Civil Eng. V. 20, pp. 26, 73, Oct. 1950.

drainage area. It is:

$$A = Ca^{2/3} \tag{2}$$

Where A is the waterway area in square feet, a is drainage area in square miles, and C is a general coefficient which varies with the watershed topography: C is 0.3 to 0.7 for flat land, 0.7 to 1.3 for rolling land, and 1.3 to 2.2 for hilly land.

Benson(9) in 1959 found that the mainstream slope is next in importance to drainage area among the factors which affect the runoff. The slope considered was for that part of the mainstream located between 85 to 10 percent of the total distance above the gaging point. The following empirical formula was found for the New England region:

$$Q = a\,A^b\,S^c \tag{3}$$

where Q is peak discharge in cfs, A is drainage area in square miles, S is the 85%-10% slope of the mainstream, and a, b, c, are the regression coefficients varying with the recurrence interval of flood.

The factors affecting the runoff may be grouped in three categories: the storm characteristics, the geomorphological and the geological characteristics of the watersheds. The dependence of the runoff on the geomorphology of the watershed is analyzed in this paper. The effect of the storm characteristics and of the soil types are considered in the following paper entitled "Design Hydrographs for Small Watersheds in Indiana". The validy of the unit hydrograph theory will ultimately be analyzed by a theoretical study of overland flow hydrodynamics.

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(9) Benson, M. A., "Channel-Slope Factor in Flood-Frequency Analysis," Jour. Hydr. Div. A.S.C.E., April 1959.

STATISTICAL ANALYSIS

The following two methods give a linear relationship between the observed variable, i.e. the discharge, and the recurrence interval or a function of the recurrence interval.

Geyer,[10] in 1940, derived a mathematical expression relating the flood magnitude to the exceedance interval

$$Y = LR^{-t^k} \qquad (4)$$

where Y is the flood magnitude in sec-ft. that has an exceedance interval of t years, and L, R, k are constants for a particular stream. Taking logarithms twice on both sides of Eq. 4, one obtains

$$\log(\log L - \log Y) = K \log t + \log \log R \qquad (5)$$

where L is then determined by trial and error so that Eq. 5 represents a straight line when log (log L - log Y) is plotted against log t.

Gumbel, [11],[12],[13] in 1941, developed the extreme value theory which is used to analyze the observed extremes and to forecast further extremes. The theory states that the probability $\Phi(x)$ for the discharge

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(10) Geyer, J. C., "New Curve-fitting Method for Analysis of Flood Records," Trans. Amer. Geophys. Union, 1940, II, pp 660-668.

(11) Gumbel, E. J., "Statistics of Extremes," New York, Columbia University Press, 1958.

(12) U. S. Dept. of Commerce, "Probability Tables for Analysis of Extreme-Value Data," National Bureau of Standards, Applied Mathematics Series 22, 1953.

(13) U. S. Dept. of Commerce, "Statistical Theory of Extreme Values and Some Practical Applications," National Bureau of Standards, Applied Mathematics Series 33, 1954.

x to be the largest among n independent observations is given by

$$\Phi(x) = e^{-e^{-y}} = \exp(-e^{-y}) \quad \text{as } n \longrightarrow \infty \tag{6}$$

where e is the base of Napierian logarithms and y, termed the reduced largest value, is given by

$$y = \alpha_n (x - u_n) \tag{7}$$

where α_n, u_n are two extreme parameters, u_n is a certain expected largest value having the return period n, and its probability $F(u_n)$ is $1 - \frac{1}{n}$; α_n is defined as $nf(u_n)$ where $f(u_n)$ is the initial distribution given by $f(u_n) = F'(u_n)$. A probability paper designed for extreme value was proposed by Powell.(14) The observed variate x is traced on the ordinate, the largest value y is traced on the abscissa, both in linear scales. The value of the probabilities $\Phi(x)$ is given in Eq. 6 or by

$$\Phi(x) = \frac{m}{n+1} \tag{8}$$

Eq. 8 gives the "plotting position" where m is the rank of the yearly maximum in increasing order, and n is the number of years of observation. The return period is given by

$$T = \frac{1}{1 - \Phi(x)} \tag{9}$$

Both the probability $\Phi(x)$ and the return period T are laid off on auxilary horizontal scales on the probability paper. Eq. 7 relating the observed variate x to the reduced largest value y may be written as

$$x = \frac{1}{\alpha_n} y + u_n \tag{10}$$

from which it appears that there is a linear relationship between x and y. Thus, theoretically, the plot of x vs y should be a straight line on probability paper.

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(14) Powell, R. W., "A Simple Method of Estimating Flood Frequencies," Civil Eng., 105-106, 1943.

Benson,[15] in 1950, made use of historical data in flood-frequency analysis. The study was made on the basis of annual peak discharges, and data were plotted on probability paper based on Gumbel's extreme value theory.

The present study includes:

1. A statistical analysis of existing peak discharge data and the determination of the 25-year flood for 32 gaged small watersheds by Gumbel's extreme value method.
2. A geomorphological analysis of 16 of these small watersheds.
3. A multiple correlation of the 25-year flood and the geomorphological characteristics. This is based on the assumption that the State of Indiana is an area sufficiently homogeneous, so that variation of storm characteristics and of physical properties of soils are not significant variables compared to the variables describing the geomorphological characteristics. The watersheds considered in this study have an area between 20 and 200 square miles approximately. These watersheds are called small because they refer to the smaller group for which flow records are reported by the U.S.G.S. They are large enough, however, so that the land use or the type of vegetation is not an important variable, and may be disregarded. This method has an advantage that the estimation of design discharges is based on the discharge records themselves, thus eliminating the need of relating rainfall and runoff by means of a number of variables difficult to evaluate.

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(15) Benson, M. A., "Use of Historical Data in Flood-Frequency Analysis," Amer. Geophy. Union Trans., V. 31, pp. 419-424, June 1950.

Flood frequency analysis for small watersheds in Indiana

Thirty-two watersheds distributed throughout the whole state were selected to study for flood frequency analysis. Fig. 1 is a map of Indiana showing the thirty-two watersheds, and Table 1 lists the names of the watersheds, their assigned number and their areas. For convenience, these numbers will be used in this report instead of the name of the watersheds. There are only three watersheds, the area of which is less than 50 square miles, 12 watersheds under 100 square miles, and 29 watersheds under 200 square miles for which flow records are available from the U.S.G.S. All of these were included in this frequency analysis. In order to have a good distribution of the watersheds over the whole state, three additional larger watersheds were included. A bar diagram was plotted in Fig. 2 to show the time period of records for each watershed.

Instantaneous annual peak flow was used for the extreme value analysis instead of the maximum mean daily flow, since it is the peak discharge that is desired for hydraulic structures design. Data for this instantaneous annual peak discharge were obtained from the U.S.G.S. office in Indianapolis, Indiana. The data are analyzed on a water year basis--that is, from October to September. The data were examined for man-made changes, such as new reservoirs, soil and water conservation works, and changes of gaging sites. It was found that no correction was needed.

Table I - List of Watersheds, Their Area and Assigned Number

Watershed No.	Gaging Station	Watershed Area (sq. mi.)
S-1	Bean Blossom Creek at Dolan, Ind.	100
S-2	Clifty Creek At Hartsville, Ind.	88.8
S-3	North Fork Vernon Fork near Butlerville, Ind.	87.3
S-4	Hart Ditch at Munster, Ind.	69.2
S-5	Salt Creek near McCool, Ind.	78.7
S-6	Little Calumet River at Porter, Ind.	62.9
S-7	Cedar Creek at Auburn, Ind.	93.0
S-8	West Creek near Schneider, Ind.	46.3
S-9	Iroquois River at Rosebud, Ind.	30.3
S-10	Bice Ditch near South Marion, Ind.	22.6
S-11	Big Slough Creek near Collegeville, Ind.	84.1
S-12	Carpenter Creek at Egypt, Ind.	48.1
1	Tippecanoe River at Oswego, Ind.	115
2	Mississinewa River near Ridgeville, Ind.	130
3	Wildcat Creek at Greentown, Ind.	162
4	Cicero Creek near Arcadia, Ind.	131
5	Fall Creek near Fortville, Ind.	172
6	Eagle Creek at Indianapolis, Ind.	179
7	Young Creek near Edinburg, Ind.	109
8	Blue River at Carthage, Ind.	187
9	Sand Creek near Brewersville, Ind.	156
10	North Fork Salt Creek near Belmont, Ind.	120
11	Patoka River at Jasper, Ind.	257
12	Busseron Creek near Carlisle, Ind.	228
13	East Fork White Water River at Richmond, Ind.	123
14	Silver Creek near Sellersburg, Ind.	188
15	Big Indian Creek near Corydon, Ind.	129
16	Kankakee River near North Liberty, Ind.	152
17	Singleton Ditch at Schneider, Ind.	122
18	Deep River at Lake George Outlet at Hobart, Ind.	125
19	Pigeon Creek at Hogback Lake Outlet near Angola, Ind.	102
20	Laughery Creek near Farmers Retreat, Ind.	248

The historical floods were included in the analysis as suggested by Benson,[15] Dalrymple,[16] in order to extend the short time records available. The recurrence interval of historical floods may be computed for the following two cases:

1. When the historical flood is higher than those for the period of record. In this case the recurrence interval of the historical flood is recorded as equal to one plus the number of years of the period for which it is the greatest. For example the 1913 historical flood in Patoka River at Jasper, Indiana (watershed No. 11) was 16,000 cfs. The period for which it was the greatest is 47 years (1913 to 1959). According to Eq. 8 the corresponding probability is $\Phi = 47/48$, and the recurrence interval, by Eq. 9 is $T = 48$ years.

2. When the historical flood is known to be the highest until a greater flood occurs during the period of record. An example of this is the 1913 historical flood in Eagle Creek at Indianapolis, Indiana (watershed No. 6). It was 19,000 cfs, and was the second highest flood. The 1957 flood was 28,800 cfs which was larger than the historical one. The recurrence interval of these floods are calculated as in Table 2:

Table 2 Calculation of Historical Floods

Floods	n	Φ	T
28,800 cfs. Max. (1913--1959)	47	47/48	48
19,000 cfs. 2nd. Flood (1913--1959)	47	46/48	24

The flood frequency analysis based on Gumble's extreme value theory was done for all 32 selected watersheds. The instantaneous annual peak discharges were plotted against the reduced value y on the probability paper, and a straight line was fitted by the method of the least squares, except for watersheds No. 4, 6, 14, 18, and 20. These were fitted by

(16) Dalrymple, Tate, "Flood-Frequency Analyses," U.S.G.S. Water Supply Paper, 1543-A, 1960.

inspection in order to give more weight to the lower points because the upper point or the historical flood plotted excessively high in comparison with the straight line pattern of the lower points. By extending these lines, the expected floods of different frequencies were obtained and listed in Table 3. An example is given as follows:

Watershed No. S-6
Gaging Station: Little Calumet River at Porter, Indiana
Computations are shown in Table 4, and plotted results are as shown in Fig. 3.

TABLE 3

The Predicted Annual Instantaneous Peak Discharge from Flood Frequency Analysis

Watershed No.	Predicted Annual Instantaneous Peak Discharge			
	25-yrs. cfs.	50-yrs. cfs.	75-yrs. cfs.	100-yrs. cfs.
S-1	11800	13800	14700	15900
S-2	12900	15000	16000	17200
S-3	20500	24000	25400	27000
S-4	3300	3750	3940	4200
S-5	2950	3420	3600	3860
S-6	1630	1800	4000	4300
S-7	1630	1800	1880	1980
S-8	2100	2350	2450	2600
S-9	465	520	540	570
S-10	835	925	960	1010
S-11	2440	2770	2900	3080
S-12	4160	4800	5100	5500
1	4160	4800	5100	1110
2	14000	16500	17400	18800
3	7400	8600	9000	9700
4	6800	7800	8300	8900
5	7700	8900	9300	10000
6	17000	19700	21000	22300
7	10500	12400	13000	14000
8	10800	12200	12800	13600
9	21500	24000	25200	26800
10	19000	22000	23300	25200
11	13500	15600	16500	17700
12	8700	9900	10300	11000
13	19800	22800	24200	26000
14	13300	15100	15900	17000
15	22300	25700	27300	29400
16	1020	1130	1170	1230
17	1270	1370	1410	1470
18	4800	5500	5700	6200
19	760	860	900	960
20	28600	33000	35000	37300

TABLE 4

Little Calumet River at Porter, Indiana

Year	Instantaneous Annual Peak Discharge Q cfs	Rank	Q cfs	Φ	y
1945	2,440	1	490	0.0625	-1.01979
1946	715	2	521	0.1250	-0.73210
1947	2,140	3	690	0.1875	-0.51520
1948	1,960	4	715	0.2500	-0.32663
1949	690	5	848	0.3125	-0.15114
1950	1,720	6	1,060	0.3750	0.01936
1951	1,360	7	1,170	0.4375	0.19034
1952	1,060	8	1,360	0.5000	0.36651
1953	521	9	1,370	0.5625	0.55275
1954	1,170	10	1,420	0.6250	0.75501
1955	3,110	11	1,720	0.6875	0.98165
1956	1,370	12	1,960	0.7500	1.24590
1957	848	13	2,140	0.8125	1.57196
1958	490	14	2,440	0.8750	2.01342
1959	1,420	15	3,110	0.9375	2.74063

Langbein and others,[17] in 1947 indicated that river floods were the results of many causes. One of the primary objectives of scientific hydrology is the segregation and evaluation of the causative factors. The climatic factor and the soil-vegetation complex are variables that exercise their principal influence on the volume of runoff. The topography of drainage basins is a reasonably permanent characteristic which influences mainly the concentration of time distribution of discharge from a drainage basin. The topographic characteristics of drainage basin cited were: area of basin, drainage density, area-distance distribution, length of basin, land slope, area-altitude distribution, and area of water surfaces.

Strahler,[18] in 1952, expressed the area-altitude relation by a hypsometric analysis. The hypsometric curve relates horizontal cross-section area of a drainage basin to relative elevation above basin mouth. By the use of dimensionless parameters, the curves can be described and compared irrespective of true scale. The area under the curve can be used to find total land mass and the mean relief of watersheds.

Strahler,[19] in 1957, made a quantitative analysis of watershed geomorphology and showed that the linear scale measurements include length of stream channel of given order, drainage density and relief. Surface and cross-sectional area of basins are length products. Dimensionless properties include stream order numbers, stream length and bifurcation ratio,

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(17) Langbein, W.B., "Topographic Characteristics of Drainage Basin," U.S.G.S. Water Supply Paper, 968-c, pp. 155, 1947.

(18) Strahler, A. N., "Hypsometric (Area-Altitude) Analysis of Erosional Topography," Bul. Geol. Soc. Amer., V.63, pp. 1117-1142, 1952.

(19) Strahler, A. N., "Quantitative Analysis of Watershed Geomorphology," Technical Report No. 13, Dept.of Geol., Columbia University, 1957.

maximum valley-side slopes, mean slopes of watershed surfaces, channel gradients, relief ratio and hypsometric curve properties.

Benson,[9] in 1959, cited the following basin characteristics: drainage area, channel slope, land slope, tributary channel slope, watershed shape factor, mean elevation, percentage of lakes, swamps and reservoirs, and drainage density. The shape factor of the watershed was represented by:

$\frac{L^2}{A}$, equivalent of basin length divided by basin width.

$\frac{L}{A}$, basin length divided by drainage area.

$\sum aL$, the summation of small subdivisions of the drainage area, each multiplied by the distance of travel to the gaging point.

In this study, the first geomorphological factor considered is the drainage area. It is the projected area of watershed, also called the catchment area. Obviously, the bigger the area of catchment the larger the amount of runoff. However, the rate of runoff is largely dependent on the slope of the land, the drainage density, and the slope of the streams. A steep land slope with high drainage density and larger slope of stream will give a higher rate of runoff than those which have smaller slope and lower drainage density. The shape of the watershed is also a factor affecting the runoff, becuase it affects the time of concentration. With a three-dimensional concept in mind, the principal geomorphological factors which can affect the amount of peak discharge are listed as following.

1. The drainage area
2. The drainage density
3. The land slope
4. The main stream slope
5. The watershed slope

Evaluation of geomorphological factors

1. Drainage Area

Area of the watershed is directly measured from topographic maps with a planimeter. It is expressed in square miles.

2. Drainage Density

Drainage density is defined as the total length of streams in the watershed divided by its total area, that is the length of streams per unit area of the watershed. It can be expressed as follows:

Drainage Density (See Figure 4)

$$D = \frac{\Sigma L}{A} \tag{11}$$

Where ΣL is the total length of streams, and A is drainage area. The length of stream is expressed in miles and is obtained from drainage maps. Since the area is expressed in square miles, the drainage density can be expressed as miles per square miles.

3. Land Slope

Since the land slope is changing from place to place in a watershed, it is difficult to find a quantitative value to represent the land slope of a whole watershed. A new parameter introduced here to replace the land slope is the mean relief of land. The mean relief is defined as the total volume of land mass above the outlet of a watershed divided by its projected area. This can be evaluated quantitatively by using the so-called hypsometric curve developed by Langbein and by others which give a dimensionless relationship between the horizontal cross-sectional drainage basin area and the elevation.

Fig. 5 shows a watershed and its horizontal projection. The maximum elevation H' may be obtained from topographic maps, and the cross-sectional area A of the watershed can be measured by planimeter. Similarly, the projected area above any height h may be obtained from topographic maps. The dimensionless plot of the relative area a/A against the relative height h/H' is called a hypsometric curve, and its general aspect is as shown in Fig. 6. From the hypsometric curve, the total volume of land mass and the mean relief can be calculated. Since the area under the hypsometric curve can be easily measured, this can be expressed as,

$$\int_0^1 \frac{a}{A} \, d\left(\frac{h}{H'}\right) = \alpha' \tag{12}$$

which is rewritten as

$$\frac{1}{AH'} \int_0^1 a dh = \alpha' \tag{13}$$

Hence the total volume of land mass is

$$V = \int_0^1 a dh = AH'\alpha' \tag{14}$$

and the mean relief is

$$H = \frac{V}{A} = \alpha' H' \tag{15}$$

It is thus seen that the mean relief is equal to the product of the area under the hypsometric curve and the maximum height over the outlet.

4. Main stream slope

The slope of the main stream can be obtained from the topographic map at several points along the length of the stream. Usually, the upper stream reaches are steeper, and the downstream reaches are flatter. The mean slope is calculated by means of the formula introduced by

Taylor and Schwarz:[20]

$$S = \left[\frac{n}{\left(\frac{1}{S_1^{1/2}} + \frac{1}{S_2^{1/2}} + \frac{1}{S_3^{1/2}} + \cdots \frac{1}{S_n^{1/2}}\right)} \right]^2 \qquad (16)$$

where n is numbers of equal reaches, S_1, S_2, S_3, --- and S_n, are the slopes of each reach. It is based on the assumption that the quantity $\frac{R^{2/3}}{n}$, which appears in the Manning formula, is the same in all reaches.

5. Watershed shape factor

The watershed shape factor is the ratio of the main stream length to the diameter of a imaginary circular watershed of equal area. Figure 7 shows two watersheds with the same area but different shape, the actual irregularly shaped watershed and the imaginary circular one. AO is measured along the main stream up to the watershed boundary line, and A'O' is calculated from the known area of the actual watershed

$$A'O' = 2\sqrt{\frac{\text{Area of actual watershed}}{\pi}} \qquad (17)$$

The shape factor is determined as

$$f = \frac{AO}{A'O'} \qquad (18)$$

Geomorphological factors of small watersheds in Indiana

The following Table 5 shows quantitatively the geomorphological factors of 16 small watersheds in Indiana, the only ones for which topographic maps were available. The stream length and stream density were obtained from the drainage maps of Indiana.[21]

20
Taylor, A. B. and Schwarz, H. E., "Unit-Hydrograph Lag and Peak Flow Related to Basin Characteristics," Trans. A.G.U., V. 33, pp. 235-246, 1952.

21
Purdue University, "Atlas of County Drainage Maps, Indiana," Joint Highway Research Project, Engineering Bulletin Extension Series. No. 97, July 1959.

TABLE 5

Watershed Characteristics and 25-Year Annual Instantaneous Peak Runoff of 16 Watersheds in Indiana

Watershed No.	25-Year Annual Instantaneous Peak Runoff Q cfs.	Watershed Characteristics				
		Area sq. mi.	Mean Relief H. ft.	Drainage Density d mi/sq mi	Shape Factor f	Main Stream Slope $S \times 10^{-4}$
S-1	11,800	100	216	10.66	2.63	9.84×10^{-4}
S-2	12,900	88.8	270	7.38	3.00	20.88
S-5	2,950	78.7	101	6.57	1.75	9.05
S-6	3,300	62.9	110	8.00	1.12	21.10
S-7	[illegible],630	93.0	79	5.10	1.47	8.29
1	880	115	65.4	3.35	1.41	2.64
6	17,000	179	195.2	7.88	2.2	13.40
7	10,500	109	86	7.02	1.94	10.39
9	21,500	156	250	9.76	2.85	10.68
10	19,000	120	237	11.20	2.18	9.90
11	13,500	257	181.5	13.95	2.87	2.95
12	8,700	228	99.8	13.20	1.93	5.43
14	13,300	188	195.8	10.47	1.35	6.21
15	22,300	129	231	8.70	2.56	10.16
18	4,800	125	84.7	4.50	1.91	6.05
19	760	102	66.1	3.16	1.93	7.93

Multiple correlation of peak discharge and geomorphological characteristics

A multiple correlation was derived between the 25-year flood and the geomorphological variables considered above. Such a correlation presumes that the area of application is meterologically and geologically homogeneous, otherwise the state should be divided into different zones in which homogeneous conditions exist.

Since the State of Indiana is relatively flat, the orographic precipitation is not a factor in the larger storms. Convectional precipitation resulting from most thunderstorms usually has a duration which is less than the time of concentration for watersheds of more than 20 square miles. Thus frontal and cyclonic precipitation are the cause of the large storms producing peak runoff. Therefore, it could be assumed that the climatological condition is homogeneous over the State of Indiana. That is, the probability of being subjected to a storm of a given frequency is almost equal for all watersheds in Indiana.

By studying the soil map(22) of the State of Indiana, it was found that the permeability varies from soil to soil. Although this would, in theory, disprove the assumption that the geological conditions are homogeneous throughout the state, one additional multiple correlation including the maximum intake rate(23) of the soil as a variable indicated that it was not significant compared to the geomorphological variables.

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(22) Belcher, D.J., Gregg, L.E., and Woods, K.B., "The Formation, Distribution and Engineering Characteristics of Soils," Joint Highway Research Project, The State Highway Commission of Indiana, and Purdue University. January, 1943.

(23) Purdue University, "A guide for Designing Sprinkler Irrigation Systems in Indiana," Agricultural Extension Service in Cooperation with Soil Conservation Service, U.S.D.A., 1955.

Multiple correlation[24] is a statistical method to find the relationship between one dependent variable and a number of independent variables. If a linear relationship exists, the method of fitting is to make the sum of the squares of the deviations of actual observations from the theoretical linear relation a minimum. This is called the method of least squares.

The general formula for multiple correlation is

$$y = a + b_1x_1 + b_2x_2 \cdots\cdots\cdots + b_kx_k \qquad (19)$$

where y is the dependent variable, x_1, x_2, x_3, --- x_k are the independent variables, and a, b_1, b_2, b_3, --- b_k, are constants obtained by solving the following simultaneous equations:

$$b_1\,S(x_1)^2 + b_2\,S(x_1x_2) + b_3\,S(x_1x_3) \cdots\cdots + b_k\,S(x_1x_k) = S(x_1y)$$

$$b_1\,S(x_2x_1) + b_2\,S(x_2^2) + b_3\,S(x_2x_3) \cdots\cdots + b_k\,S(x_2x_k) = S(x_2y)$$

$$b_1\,S(x_3x_1) + b_2\,S(x_3x_2) + b_3\,S(x_3^2) \cdots\cdots + b_k\,S(x_3x_k) = S(x_3y)$$

$$\vdots$$

$$b_1\,S(x_kx_1) + b_2\,S(x_kx_2) + b_3\,S(x_kx_3) \cdots\cdots + b_k\,S(x_k^2) = S(x_ky)$$

and

$$a = \bar{y} - b_1\bar{x}_1 - b_2\bar{x}_2 - b_3\bar{x}_3 \cdots\cdots - b_k\bar{x}_k \qquad (20)$$

where $S(xy)$ is a symbol which means $\sum xy - \frac{\sum x \sum y}{n}$

so that

$$S(x_1^2) = \sum x_1^2 - \frac{(\sum x_1)^2}{n}$$

$$S(x_1x_2) = \sum x_1 x_2 - \frac{\sum x_1 \sum x_2}{n}$$

$$S(x_1x_k) = \sum x_1x_k - \frac{\sum x_1 \sum x_k}{n}$$

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24 Bennett, C. A. and Franklin, N. L., "Statistical Analysis in Chemistry and the Chemical Industry," John Wiley & Sons, Inc. 1954.

The general formula for estimate of variance is

$$s^2_{y,\ x_1,\ x_2,\ x_3\ \cdots\cdots\cdots\cdots\ x_k} = \frac{S(y^2) - b_1\, S(x_1 y) - b_2\, S(x_2 y) \cdots\cdots - b_k\, S(x_k y)}{n - (k + 1)} \qquad (21)$$

where k is number of independent variables.

This serves as a measure of the degree of correlation. Generally the smaller the variance, the better the correlation.

The following Table 6 shows the results of correlation between the 25-year instantaneous peak discharge and the geomorphological factors of small watersheds in Indiana. The regression formulas in exponential type as shown in Table 6 were obtained by means of a logarithmic transformation and the formulas (19) and (20). The standard deviation were calculated by means of Eq. (21).

Table 6 - Multiple Correlation between Predicted 25-years Instantaneous Peak Discharge and Geomorphological Factors

Discharge	Geomorphological Factors	Regression Formula	Standard* Deviation
Q	A, f	$Q = 30.29\, A^{0.8471}\, f^{1.9245}$	0.394
	A, S	$Q = 0.0005716\, A^{2.6792}\, S^{1.5729}$	0.305
	A, D	$Q = 47.13\, A^{0.1994}\, D^{1.9847}$	0.296
	A, H	$Q = 0.03993\, A^{0.7220}\, H^{1.7396}$	0.234
Q	A, H, t	$Q = 0.49\, A^{0.7066}\, H^{0.1701}\, f^{0.1100}$	0.243
	A, H, D	$Q = 0.3432\, S^{0.3036}\, H^{1.2732}\, D^{0.8601}$	0.213
	A, H, S	$Q = 0.0072\, S^{1.4628}\, H^{1.3035}\, S^{0.6938}$	0.211
Q	A, H, S, f.	$Q = 0.0057\, A^{1.3915}\, H^{1.0825}\, S^{0.7114}\, f^{0.6339}$	0.217
	A, H, S, D	$Q = 0.02337\, A^{1.0513}\, H^{0.9672}\, S^{0.5890}\, D^{0.7417}$	0.199
Q	A, H, S, D, f	$Q = 0.05363\, A^{0.9715}\, H^{0.7844}\, S^{0.5901}\, D^{0.8234}\, f^{0.4160}$	0.190

* in Log-unit.

A whole set of multiple correlations was listed in Table 6. By studying the standard deviations, it is easy to find the significance level of geomorphological factors which affect the discharge. If A is assumed to be the first in significance to influence the discharge, then the H will be the second one, and S, D, f will be the third, fourth and last respectively. The last regression formula in Table 6,

$$Q = 0.05363\, A^{0.9715}\, H^{0.7844}\, D^{0.8234}\, f^{0.4160}\, S^{0.5901} \quad (22)$$

with the least standard deviation is of course the best expression obtained from multiple correlation. If all the geomorphological factors with their powers together are combined as a "basin characteristic", B,

$$B = A^{0.9715}\, H^{0.7844}\, D^{0.8234}\, f^{0.4160}\, S^{0.5901} \quad (23)$$

then, the regression formula can be expressed as Q = cB, where c is a constant. This is the equation of a straight line on log-log paper as shown in Figure 8. A 95% confidence interval was calculated and plotted. The probability of any observation falling between these intervals is 95%.

To test the assumption of geological homogeneity an additional multiple correlation was made including a variable representing soil characteristics. The maximum intake rate (23) of the soil expressed in inches per hour was selected as the new variable in addition to the five geomorphological variables used before. The six variable multiple correlation which would take care of the nonhomogeneous condition of the watershed geology did not show much improvement in the degree of correlation to the peak discharge, having a standard deviation somewhat larger than that for Eq. (22). This is because the variation in the intake rate is small for the watersheds studied. Until additional data on runoff from small watersheds becomes available, Eq. (22) is the best relationship that can be derived between peak flow and physiographic factors.

Construction of correlation chart for predicting future flood

The regression formula, Eq. (22) or its graphical representation in Figure 8 may be used to calculate the flood discharge if the geomorphological factors are known. A nomographic representation of the regression formula, Eq. (22), was prepared. From this it is possible to obtain directly the flood discharge from the known geomorphological factors.

The regression formula has the form

$$Q = KA^a\ B^b\ C^c\ D^d\ E^e \qquad (24)$$

Letting

$$M_1 = A^a\ B^b$$

$$M_2 = A^a\ B^b\ C^c = M_1\ C^c$$

$$M_3 = A^a\ B^b\ C^c\ D^d = M_2\ D^d$$

then

$$Q = KA^a\ B^b\ C^c\ D^d\ E^e = KM_3E^e$$

The above equations may be plotted with B, C, D, E as parameters and b, c, d, e are known exponents of the regression formula as shown in Figure 9. The diagrams of Fig. 9 may be combined; the "A^a" scale is changed from "A" scale so that the area A can be introduced directly into the chart along with the other factors necessary to find the flood discharge, as shown in Figure 10.

The above procedure was used to prepare the nomograms of Figures 11 and 12. These may be used instead of Eq. 22 or of Figure 8 to estimate the 25-year peak discharge from the geomorphological characteristics. Fig. 11 was prepared for watersheds less than 100 square miles and in Fig. 12, the correlation is extrapolated to cover watersheds up to 300 square

miles. Two examples are presented to show the use of the charts:

(a)

Watershed No.		S-6
Watershed area	(A)	62.9 sq. mi.
Mean relief	(H)	110 ft.
Drainage density	(D)	8 mi./sq. mi.
Shape factor	(f)	1.12
Main Stream slope	$(S) \times 10^{-4}$	21.10×10^{-4}

Following the dotted line in Fig. 11, the flood discharge is read from the chart directly as 3,750 cfs., while the flood predicted by the frequency study is 3,300 cfs.

(b)

Watershed No.		S-1
Watershed area	(A)	100 sq. mi.
Mean relief	(H)	216 ft.
Drainage density	(D)	10.66 mi./sq. mi.
Shape factor	(f)	2.63
Main stream slope	$(S) \times 10^{-4}$	9.84×10^{-4}

Following the dotted line in Fig. 12, the flood discharge reading is 12,750 cfs., while the flood predicted by the frequency study is 11,800 cfs.

A simple approximate estimation of peak discharge for small watersheds in Indiana.

As shown in the previous paragraphs, equation (22) is the best one among the 10 formulas listed in Table 6 for predicting the peak discharge for small watersheds in Indiana since it has the least standard deviation. Although a graphical representation of the correlation formula, Eq. 22 is given, its use is time consuming because of the tedious work required for the determination of the five geomorphological factors which enter into the formula or in the correlation charts as independent variables. In particular the determination of the drainage density D and of the mean relief H are time consuming. For the multiple correlations listed in Table 6, it appears that the formula containing A, H and S has a standard deviation of 0.211 which is close to the standard deviation of 0.190 for Eq. 22 and may therefore be used as a good approximation in practical design. This formula eliminates the need of calculating the drainage density D, and the watershed shape factor f which is the least significant variable is omitted. The formula

$$Q = 0.0022\ A^{1.462}\ H^{1.3035}\ S^{0.6938} \qquad (25)$$

still requires the determination of the mean relief H of the watershed. However, there is an approximate way of determining H by estimating α', the area under the hypsometric curve. The average hypsometric curves have been plotted for small watersheds in Indiana in Fig. 13, from which it appears that the α'- values vary from 0.4 to 0.8. From the pattern of the hypsometric curves it is possible to estimate α' by calculating only one value of a/A for a certain elevation ratio, say h/H' = 0.5. Thus two area measurements are needed: the total area of the watershed A, and the area at an elevation half way between the maximum elevation and the mouth. The following Table 7 gives the α' values for corresponding a/A:

Table 7 – The α values corresponding to a/A for h/H' = 0.5

a/A	α
0.3	0.40
0.4	0.45
0.5	0.50
0.6	0.55
0.7	0.60
0.8	0.70
0.9	0.90

For a rough estimate of α', it may be assumed that it varies between 0.4 to 0.[illegible] for U-shape valleys and from 0.6 to 0.7 for V-shape valleys in Indiana. With the value of determined from Table 7, the mean relief H can be easily calculated from α' Eq. 1, and the peak discharge can be obtained by Eq. 25 .

Thus, the peak discharge can be calculated [illegible] three methods. The first is the simplest; α' is obtained from Table 7, from which by Eq. 15 and Eq. 25 a first approximation of the peak discharge is obtained. In the second method H is determined by plotting the hypsometric curve and Eq. 25 is used as a second approximation of the peak discharge. The third method requires the evaluation of the five geomorphological factors, after which the peak discharge is calculated by Eq. 22 or by means of Figures 11 and 12.

An example is given below and solved by the three methods.

Watershed No. S-1

First Method:

geomorphological factors

A = 100 square miles

S = 9.84

$H' = 400$ feet

at $h/H' = 0.5$, $a/A = 0.573$, from Table 7, $\alpha' = 0.53$

$H = 400 \times 0.53 = 212$ feet

By Eq. 25, the 25-year peak discharge is

$Q = 9,280$ cfs.

Second Method:

geomorphological factors

$A = 100$ square miles

$S = 9.84$

$H = 216$ feet

by Eq. 25, the 25-year peak discharge is

$Q = 9,480$ cfs.

Third Method:

The 25-year peak discharge was found by using the regression formula, Eq. 22 or Figures 11 and 12 as shown in the previous example relating to those charts, is

$Q = 12,450$ cfs.

while the 25-year peak discharge estimated from the frequency study was 11,800 cfs.

Comparing the results obtained by the three methods to the peak discharge obtained from the frequency study, it appears that the percentages of error are respectively -21.4%, -19.7%, and +5.5%. It should be remembered however that these percentage will vary from one watershed to the next as methods 1 and 2 are calculated by means of one regression formula whereas method 3 is obtained by a different regression formula.

Relationship between 25-year peak discharge and the peak discharge for other frequencies.

In the preceding paragraphs, the peak discharges from small watersheds were obtained for a recurrence interval of 25-years which was based on the average life of small highway drainage structures. However, it may be desirable to estimate the peak discharge for other return periods so that the design engineer may have a greater freedom of choice. Hence the relationship between the peak discharge for any frequency and the 25-year peak discharge was derived for small watersheds in Indiana. The theoretical relationship is based on Gumbel's extreme value theory. Figure 14 shows two theoretical straight lines for any two watersheds. The differences between the 25-year peak discharge and the n-year peak discharge for the two watersheds are obtained from Eq. (10), and are:

$$\Delta Q_1 = \frac{1}{\alpha_1} \Delta y$$

$$\Delta Q_2 = \frac{1}{\alpha_2} \Delta y \qquad (26)$$

where $1/\alpha_1$, $1/\alpha_2$, are the slopes of the straight lines, and the increment Δy of the reduced variate corresponds to the selected increment of frequency. For a fixed frequency n the increment Δy is a constant. A general form thus can be written for all the watersheds as

$$\Delta Q = \frac{1}{\alpha} \Delta y \qquad (27)$$

or

$$\alpha Q_n - \alpha Q_{25} = \Delta y$$

$$\alpha Q_n = \alpha Q_{25} + \Delta y$$

$$= \alpha Q_{25} \left(1 + \frac{\Delta y}{\alpha Q_{25}}\right)$$

thus

$$Q_n = Q_{25} \left(1 + \frac{\Delta y}{\alpha Q_{25}}\right) \qquad (28)$$

Taking logarithms on both sides

$$\log Q_n = \log Q_{25} + \log \left(1 + \frac{\Delta y}{\alpha Q_{25}}\right) \tag{29}$$

Eq. 29 is a linear on log-log paper, if the last term is constant. An examination of the last term shows firstly that the $\frac{\Delta y}{\alpha Q_{25}}$ is small compared to "1" and secondly that the value of αQ_{25} for most of the small watersheds in Indiana varies from 4 to 6 and an average value of 5 can be used for αQ_{25} for small watersheds in Indiana. Then, Equation 29 becomes

$$\log Q_n = \log Q_{25} + \log \left(1 + \frac{\Delta y}{5}\right) \tag{30}$$

Values of Δy for several design frequencies are given in Table 8. Values of Δy for other frequencies may be obtained from Fig. 3.

Table 8. Values of Δy for different frequencies.

n	Δy
10	-0.93
50	0.70
75	1.00
100	1.40

Fig. 15 is a plot of Eq. 30 on logarithmic paper, giving the relationship between the 25-year peak discharge and the peak flow for frequencies of 10, 50, 75 and 100 - years. Such peak discharges may be determined from Fig. 15 or from Eq. (30) if the 25-year discharge has previously been determined from Figures 11 and 12 or from Eq. (22).

DISCUSSION AND CONCLUSIONS

1. The paper considers watersheds between 20 and 200 square miles in area in the state of Indiana. All available past observations of annual peak discharge were plotted on a probability paper using Gumbel's extreme value theory. As there is a linear relation between the observations and the reduced largest value y, the best fit straight line was then obtained. Future floods with different frequencies were obtained by extending the straight line. Table 3 gives the predicted flood of 25, 50, 75 and 100 years frequency for 32 gaged watersheds in Indiana.

2. The quantitative study of geomorphological factors of small watersheds in Indiana combined with the use of multiple correlation techniques gives an indirect determination of peak discharge. This is based on the assumption that the climatological and geological conditions are homogeneous throughout the state. Hence, the geomorphological characteristics are the dominant factors which affect the peak discharge from small watersheds. The geomorphological factors considered significant are: the watershed area, the drainage density, the mean relief of watershed, the main stream slope, and the shape factor of the watershed.

3. Correlation charts (Figs. 11 and 12) were prepared to obtain the 25-year peak discharge directly from the five watershed characteristics, for areas up to 300 square miles. As shown in the previous examples, the design engineers may use these design charts to estimate very rapidly the 25-year peak discharge with good accuracy. The peak discharge for other frequencies may be obtained from Fig. 15.

4. A simple formula which contains only three geomorphological factors, A, H, and S was introduced as a first-approximation. H is determined by the α - value which is estimated from the average hypsometric curves for small watersheds in Indiana.

ACKNOWLEDGMENT

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Appendix - Notations

A	Area of watershed, sq. miles
a	Area of watershed for a given elevation h, sq. miles
D	Drainage density (see. eq. 11), miles/sq. miles
f	Watershed shape factor (see eq. 18)
H'	Maximum height of watershed above the mouth, ft.
H	Mean relief of watershed (see eq. 15), ft.
h	The height above the mouth of any given point on the watershed, ft.
ΣL	Total length of streams on the watershed, miles
m	Rank of the yearly maximum in increasing order
n	Numbers of independent observations
Q	Peak discharge, cubic feet per second
Q_{25}	25-year peak discharge, cubic feet per second
Q_n	n-year peak discharge, cubic feet per second
S	Mean slope of main stream (see eq. 16)
T	The return period, years
u_n	A certain expected largest value having the return period n (see eq. 7)
V	Total volume of land mass of watershed, (see eq. 14)
x	Any independent observation of the peak discharge
y	Reduced largest value (see eq. 7)
$\Phi(x)$	Probability of x being the largest among n independent observations (see eq. 6 and 8)
α'	Area under hypsometric curve (see eq. 12)
α	An extreme value parameter (see eq. 7)

List of Figures

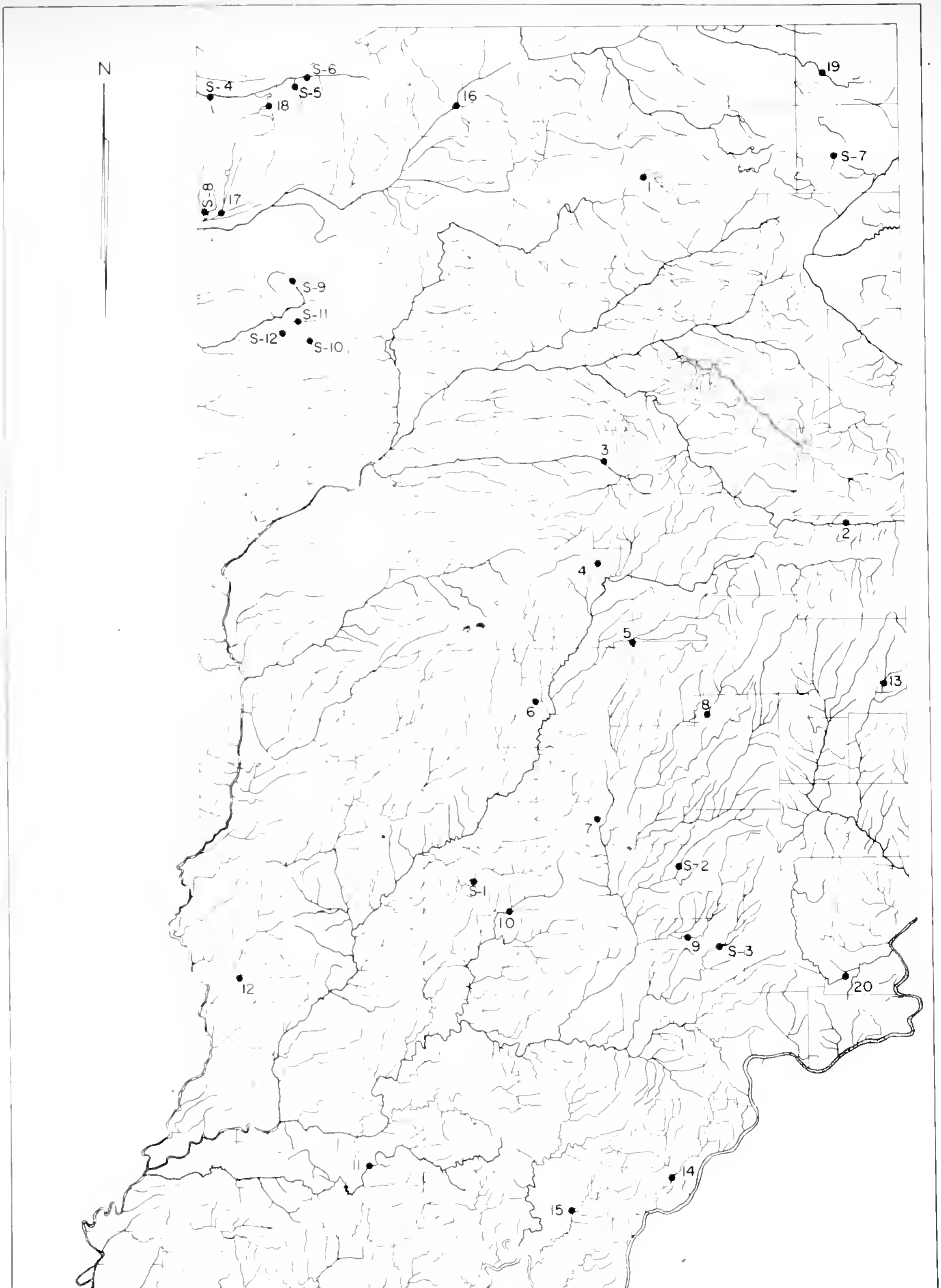
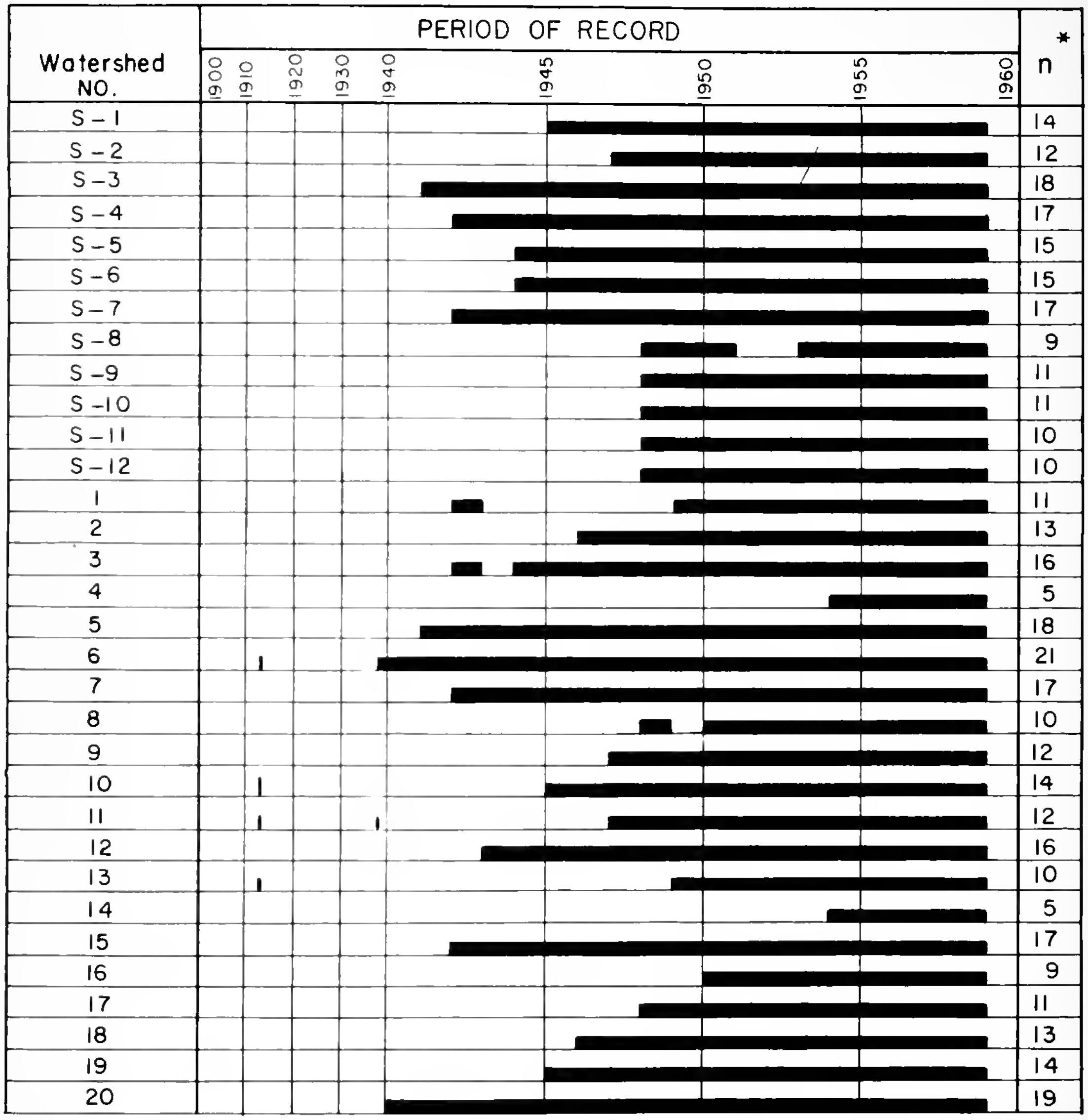
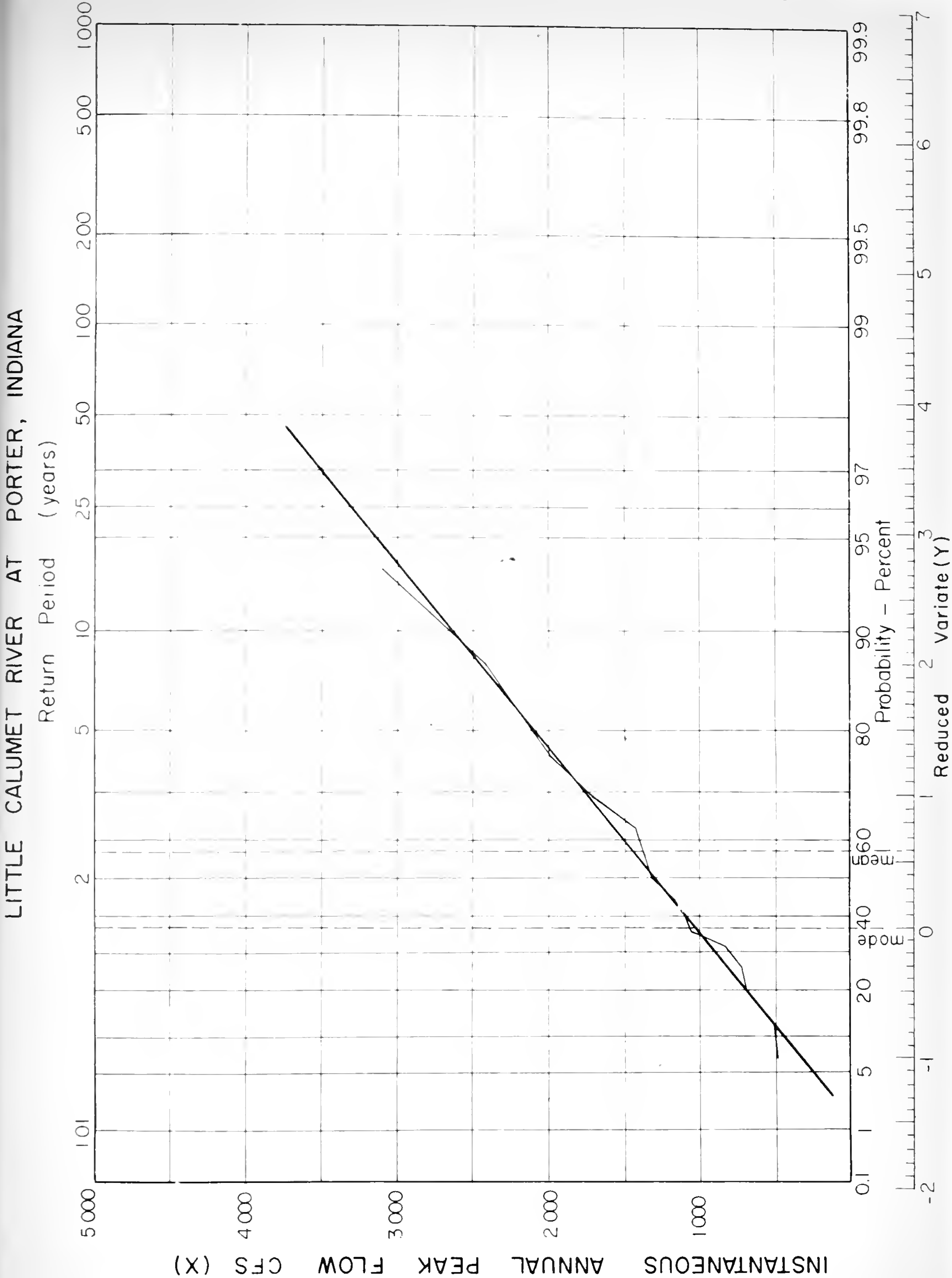

N
S-4
S-6
S-5
18
16
19
S-7
1
S-8
17
S-9
S-11
S-12
S-10
3
2
4
5
13
8
6
7
S-2
S-1
10
9
S-3
20
12
11
14
15

Fig. 2 PERIOD OF RECORD OF INSTANTANEOUS ANNUAL PEAKS AT GAGING STATIONS.

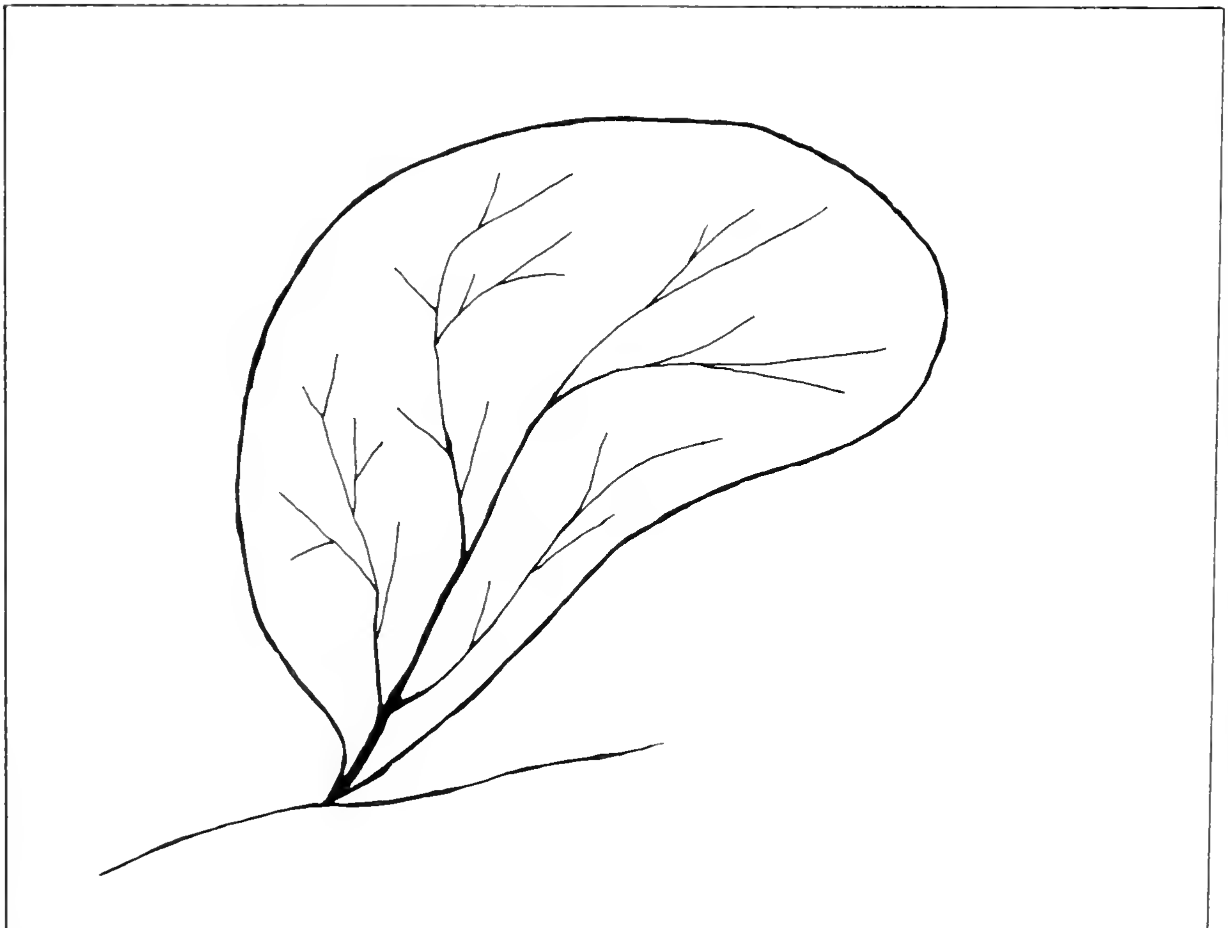


* n = Length of Record in Years

FIG. 3


LITTLE CALUMET RIVER AT PORTER, INDIANA
Return Period (years)
1.01
2
5
10
25
50
100
200
500
1000
Probability – Percent
0.1
1
5
20
40
60
80
90
95
97
99
99.5
99.8
99.9
mode
mean
Reduced Variate (Y)
-2
-1
0
1
2
3
4
5
6
7
INSTANTANEOUS ANNUAL PEAK FLOW CFS (X)
1000
2000
3000
4000
5000

WU & DELLEUR FIG. 4



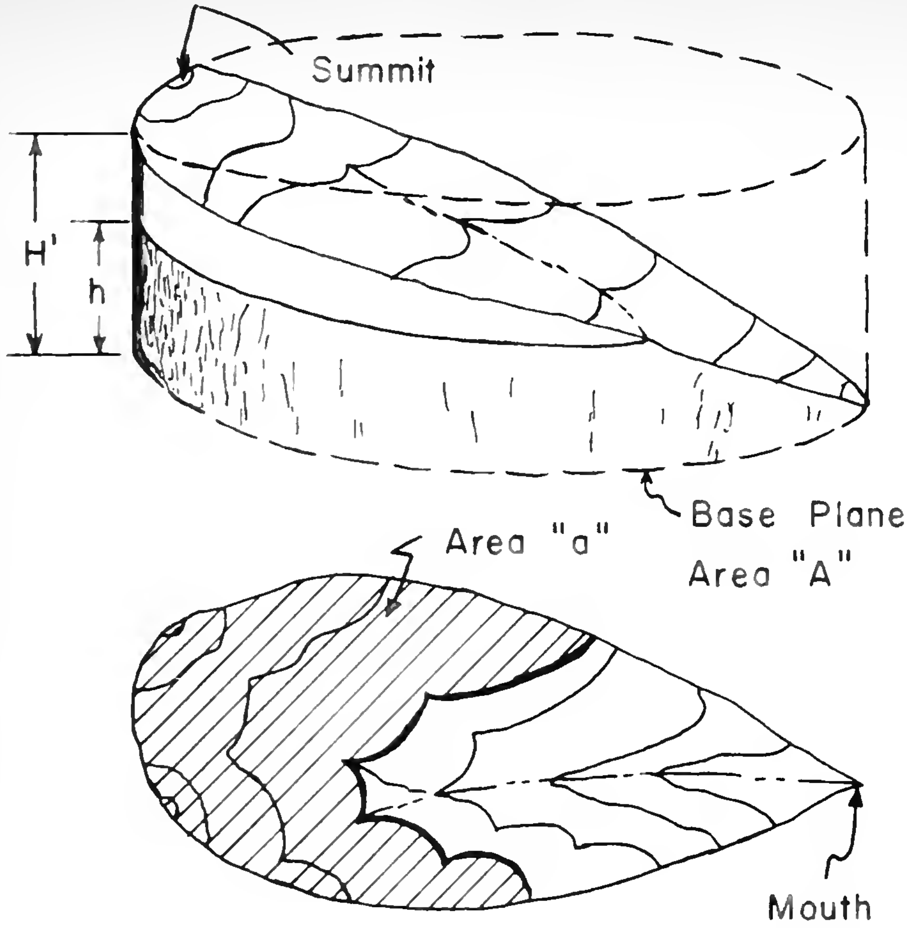

Summit
H'
h
Base Plane
Area "A"
Area "a"
Mouth

FIG. 5

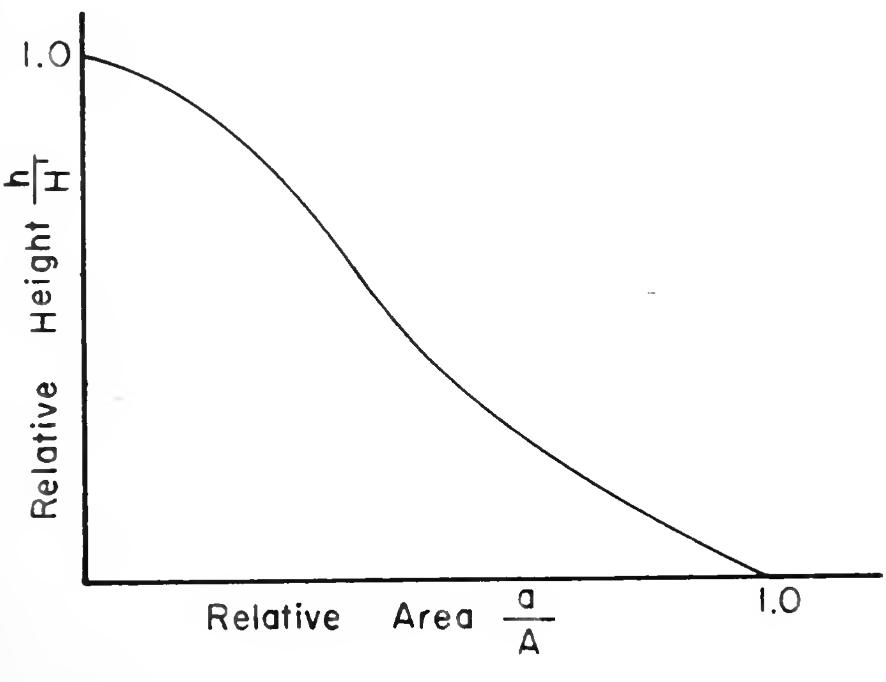
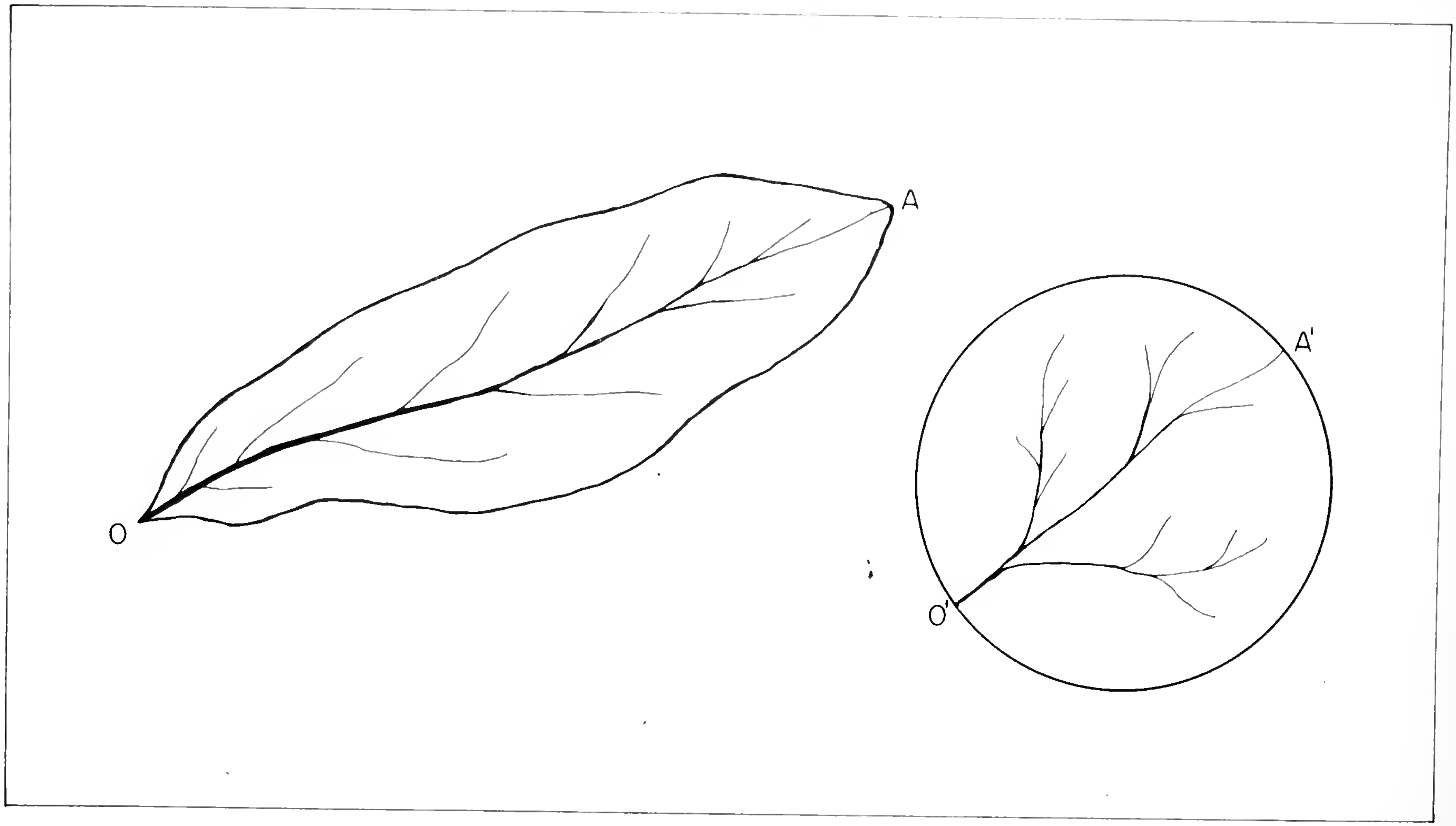
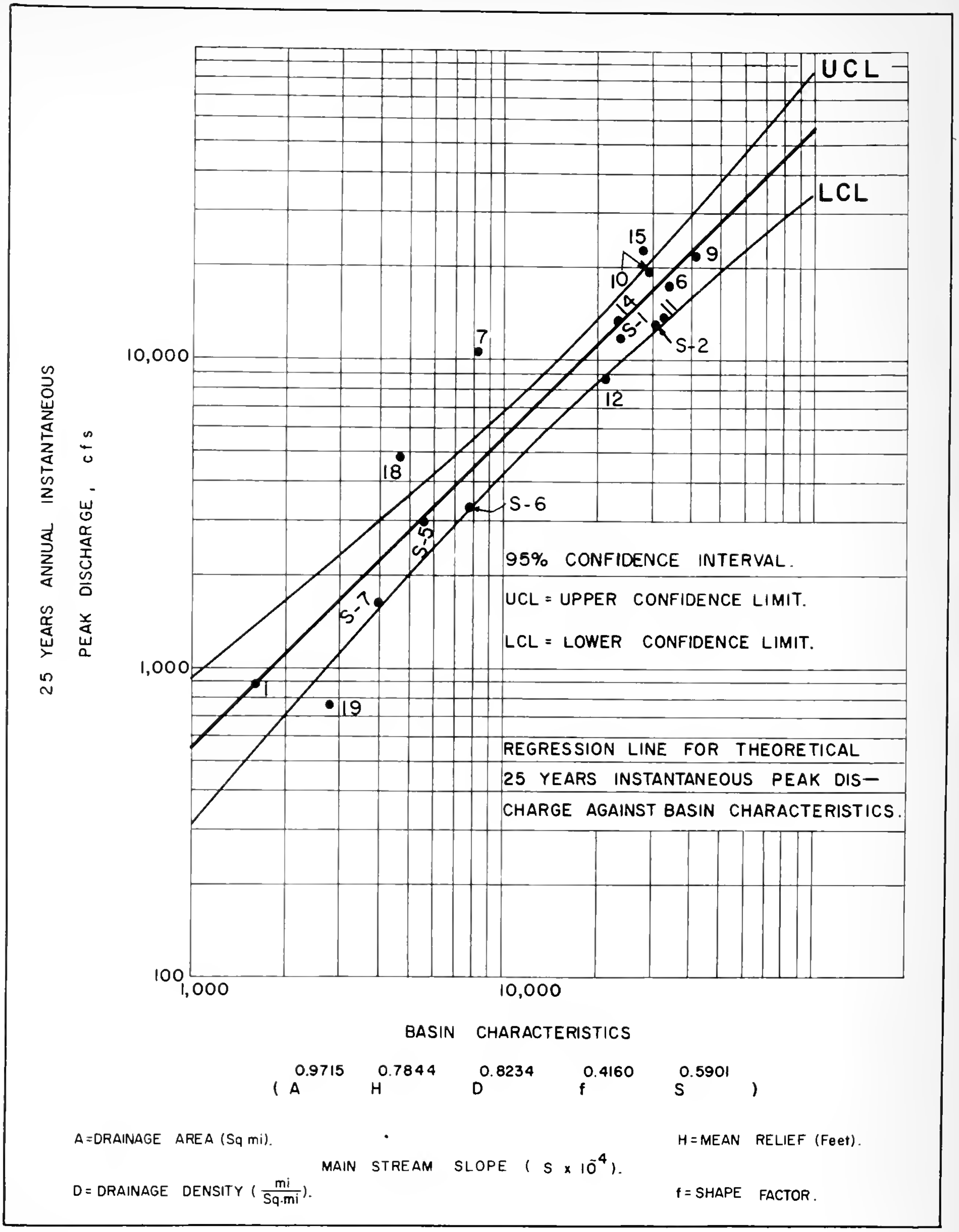

1.0
Relative Height $\frac{h}{H}$
Relative Area $\frac{a}{A}$
1.0

FIG. 6

WU & DELLEUR FIG. 7



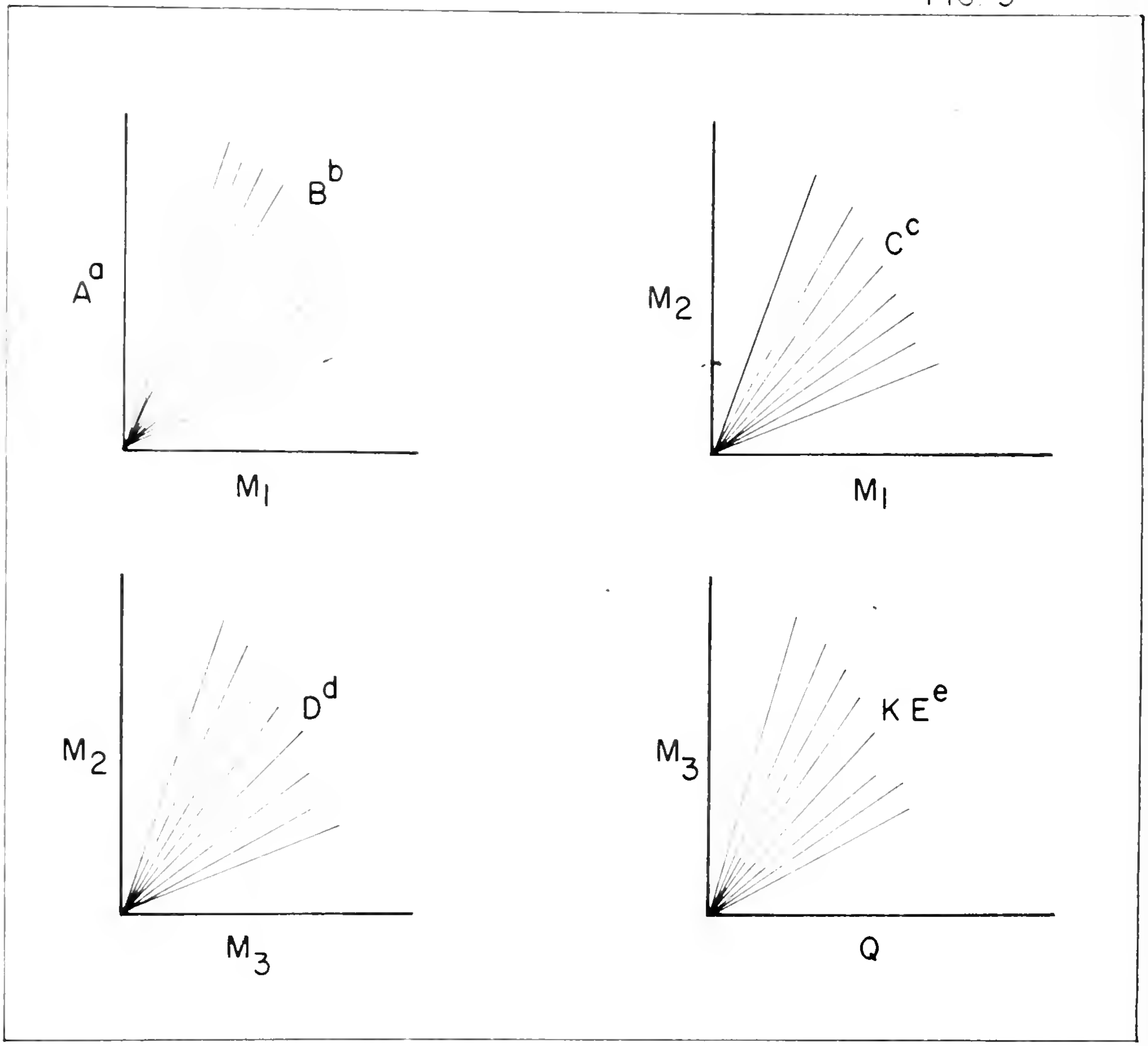


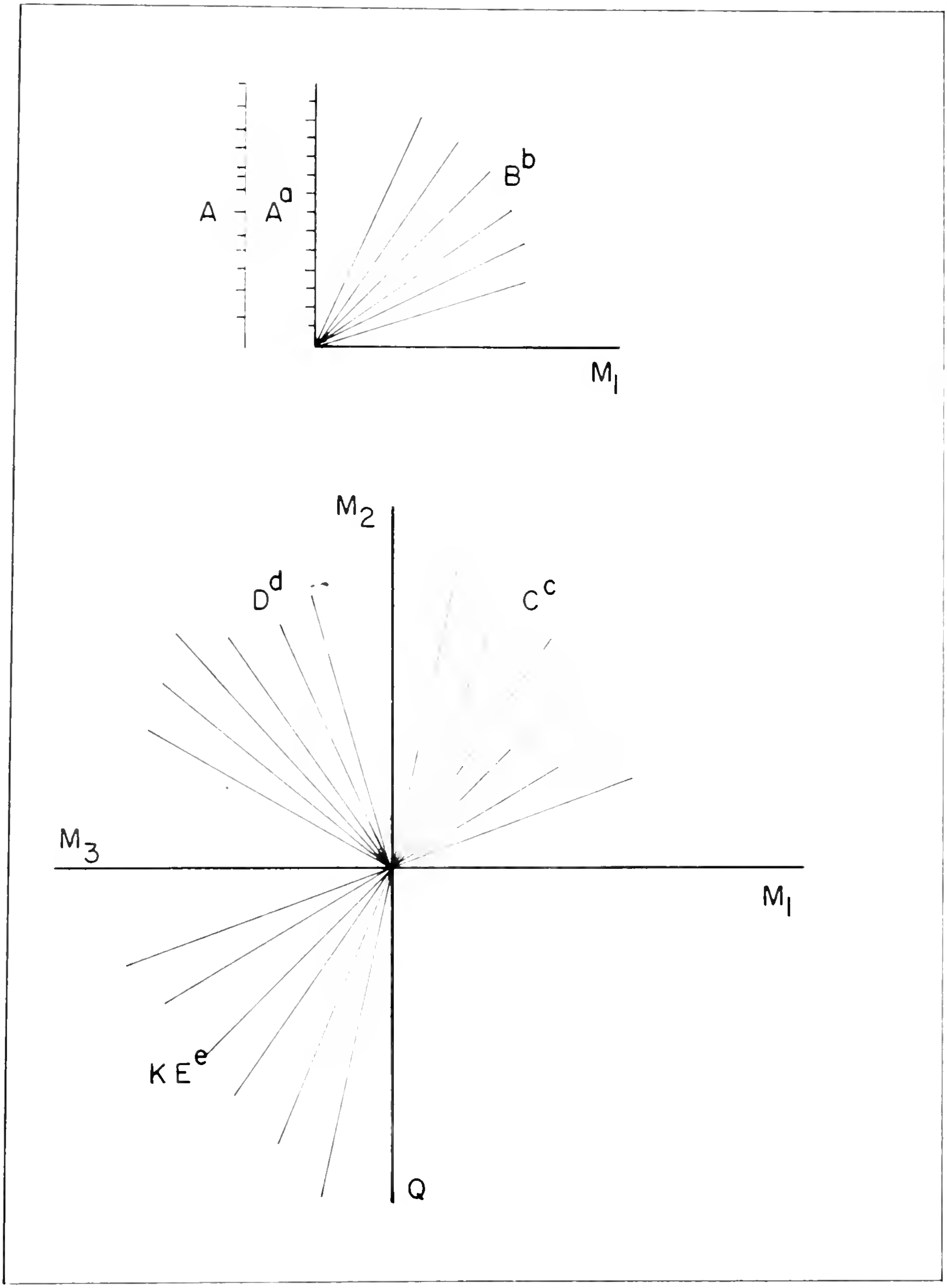
UCL
LCL
10,000
1,000
100
1,000
10,000
25 YEARS ANNUAL INSTANTANEOUS PEAK DISCHARGE, cfs
15
9
10
6
14
11
S-1
S-2
7
12
18
S-6
S-5
S-7
1
19
95% CONFIDENCE INTERVAL.
UCL = UPPER CONFIDENCE LIMIT.
LCL = LOWER CONFIDENCE LIMIT.
REGRESSION LINE FOR THEORETICAL 25 YEARS INSTANTANEOUS PEAK DISCHARGE AGAINST BASIN CHARACTERISTICS.
BASIN CHARACTERISTICS
$(A^{0.9715} H^{0.7844} D^{0.8234} f^{0.4160} S^{0.5901})$
A = DRAINAGE AREA (Sq mi).
H = MEAN RELIEF (Feet).
MAIN STREAM SLOPE ($S \times 10^{-4}$).
D = DRAINAGE DENSITY ($\frac{mi}{Sq.mi}$).
f = SHAPE FACTOR.

FIG. 8

WU & DELLEUR

FIG. 9




A
A^a
B^b
M1
M2
D^d
C^c
M3
M1
KE^e
Q

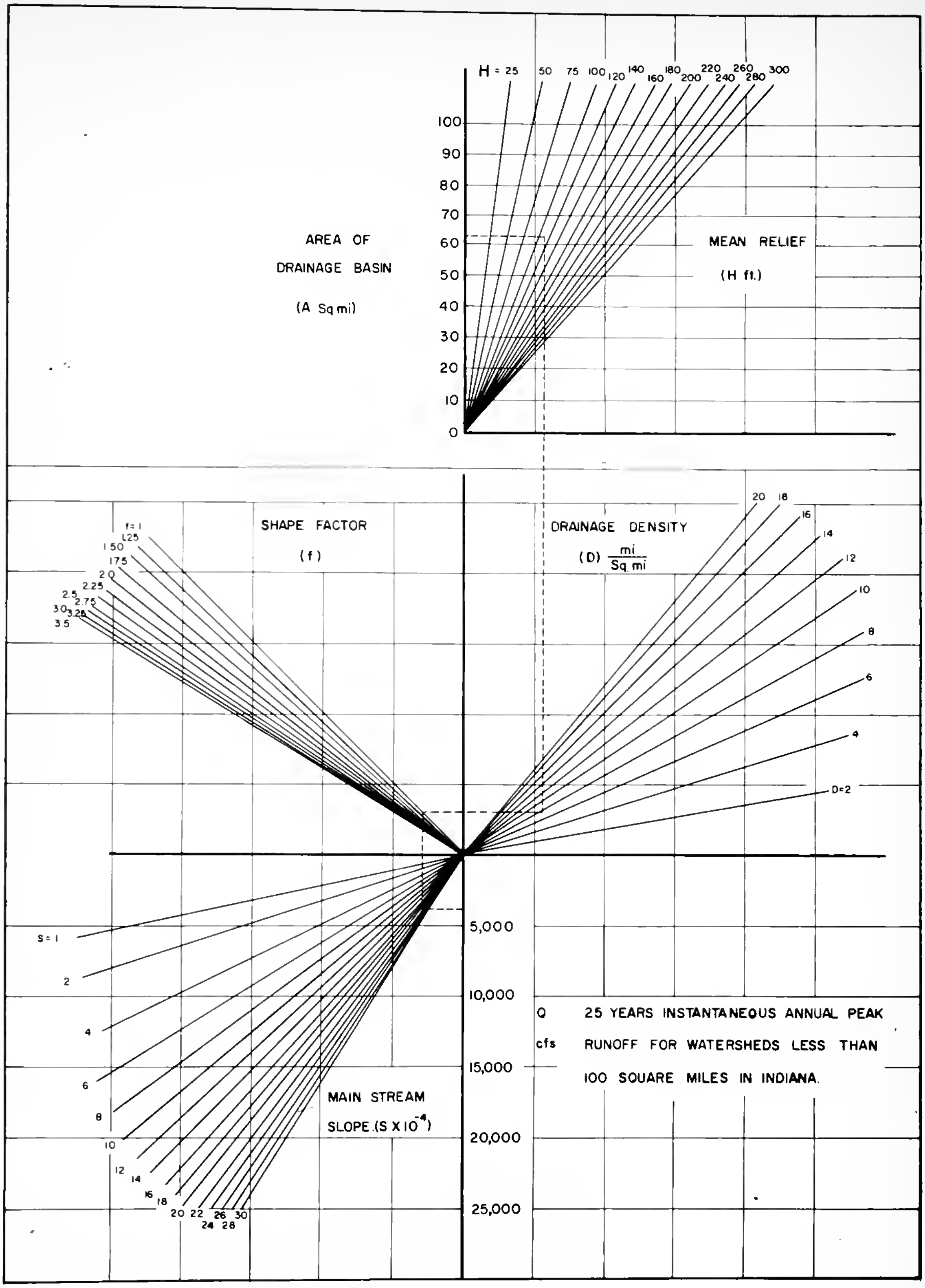

H = 25 50 75 100 120 140 160 180 200 220 240 260 280 300
AREA OF DRAINAGE BASIN (A Sq mi)
0 10 20 30 40 50 60 70 80 90 100
MEAN RELIEF (H ft.)
SHAPE FACTOR (f)
f = 1 1.25 1.50 1.75 2.0 2.25 2.5 2.75 3.0 3.25 3.5
DRAINAGE DENSITY (D) mi/Sq. mi
D = 2 4 6 8 10 12 14 16 18 20
MAIN STREAM SLOPE (S X 10^-4)
S = 1 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30
5,000
10,000
15,000
20,000
25,000
Q cfs
25 YEARS INSTANTANEOUS ANNUAL PEAK RUNOFF FOR WATERSHEDS LESS THAN 100 SQUARE MILES IN INDIANA.

FIG. 11

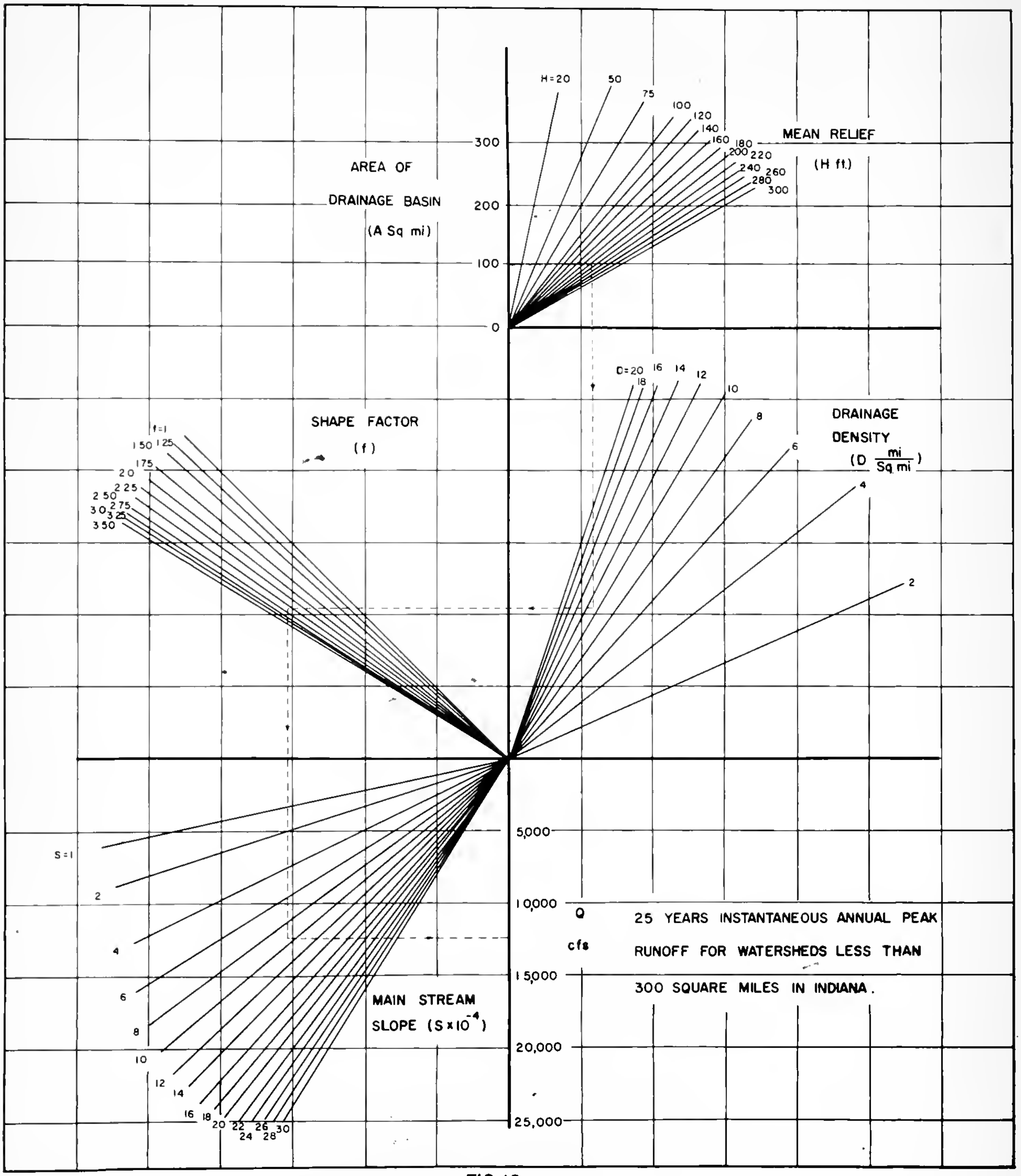
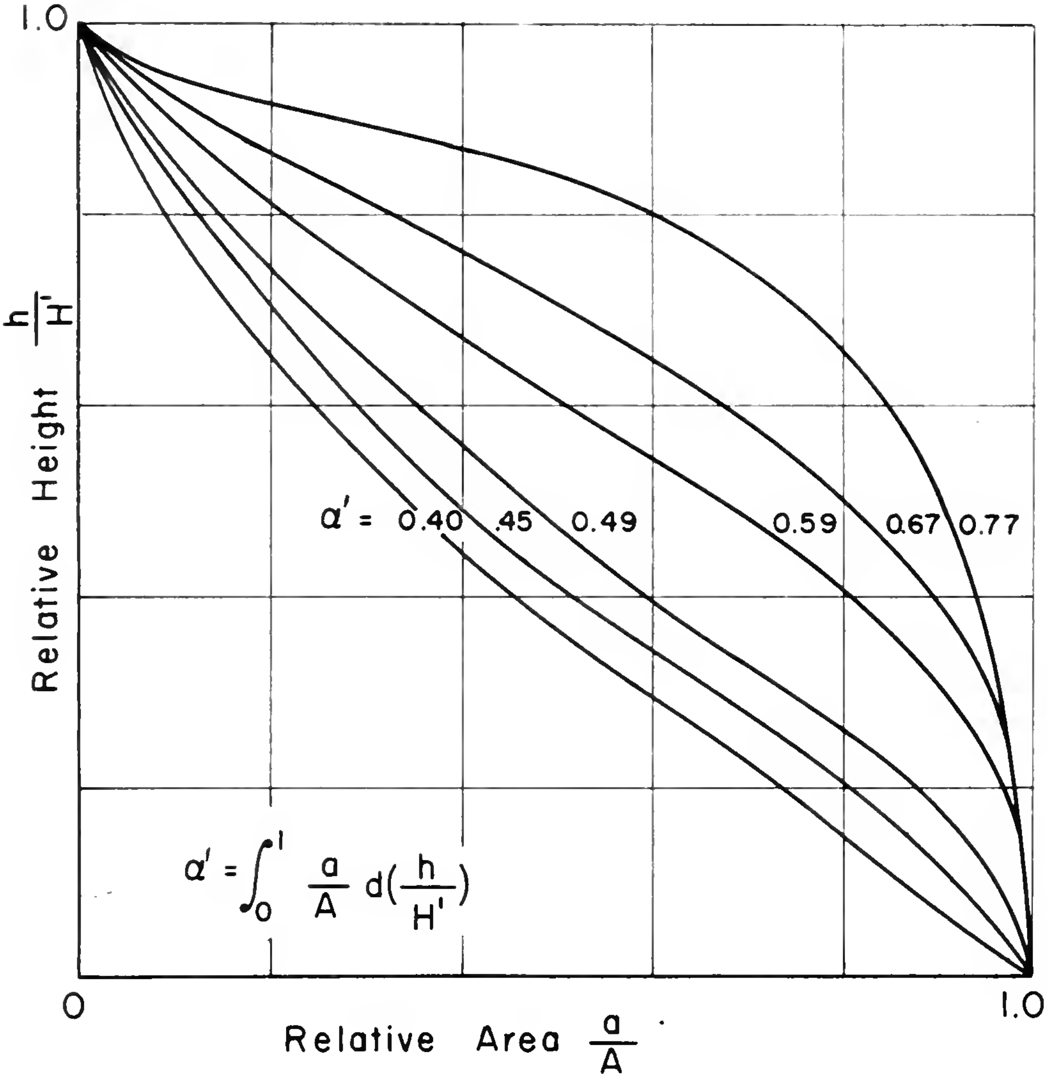
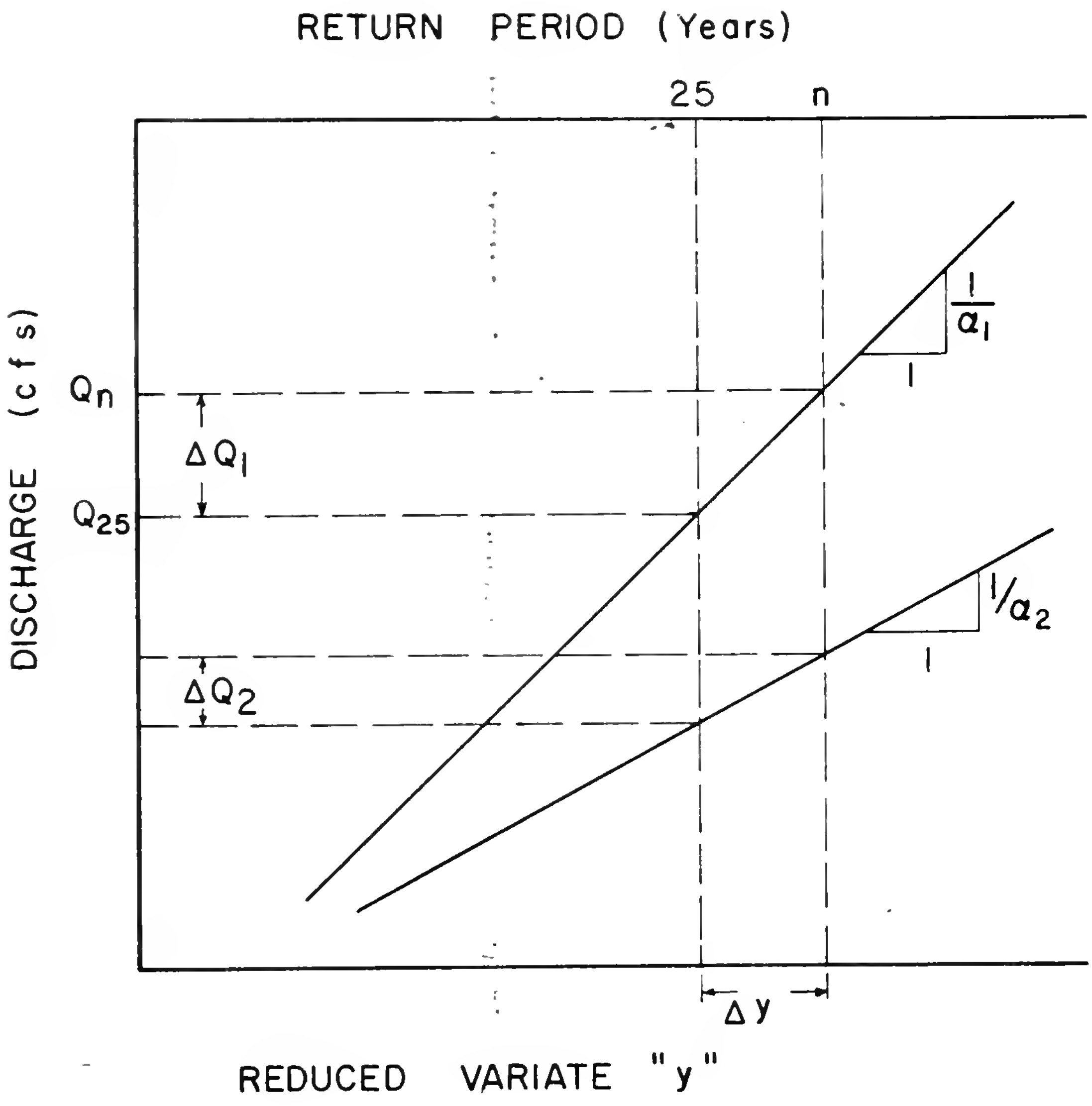
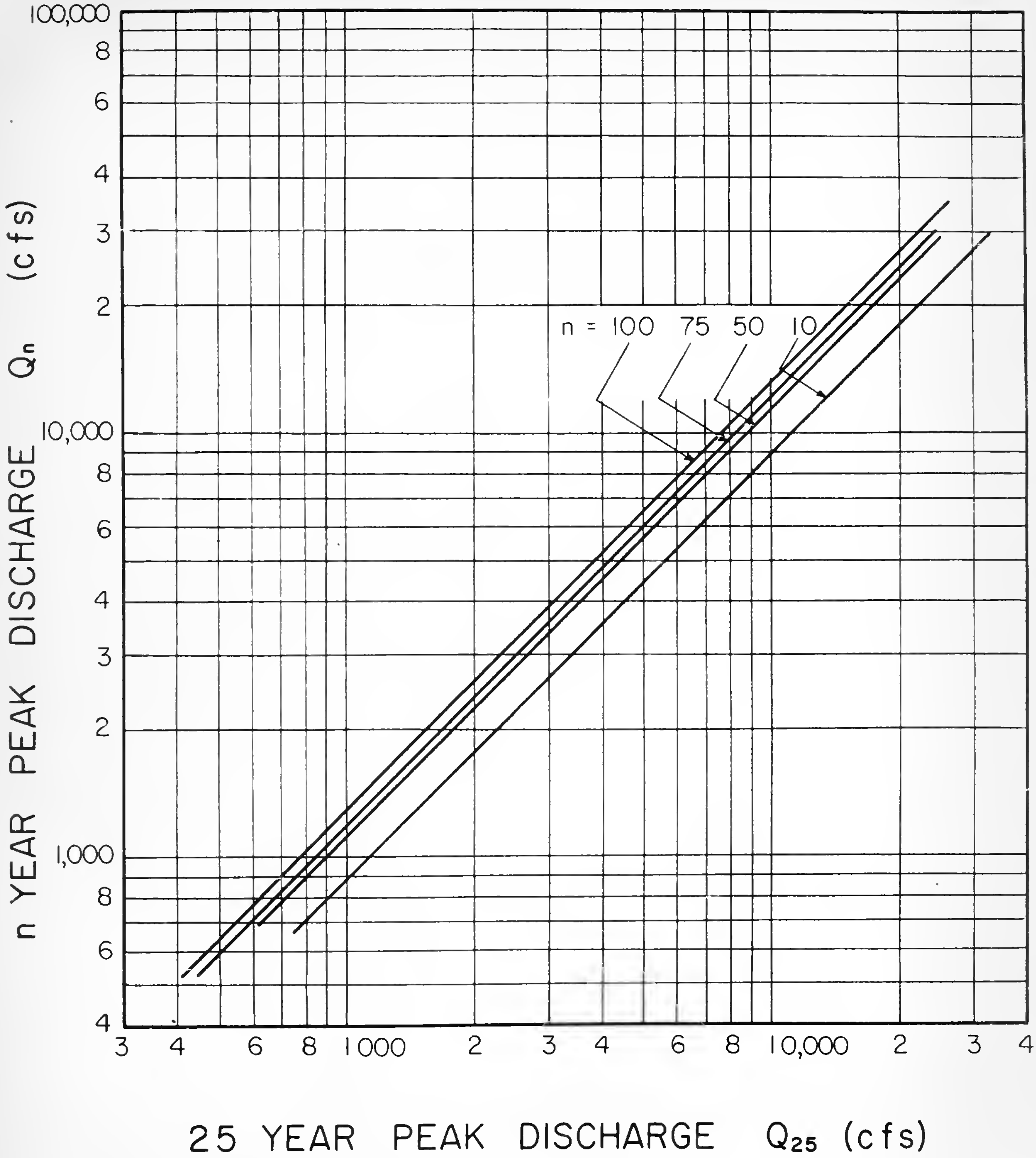

AREA OF
DRAINAGE BASIN
(A Sq mi)
MEAN RELIEF
(H ft.)
SHAPE FACTOR
(f)
DRAINAGE
DENSITY
(D mi/Sq mi)
MAIN STREAM
SLOPE (S x 10^-4)
Q
cfs
25 YEARS INSTANTANEOUS ANNUAL PEAK
RUNOFF FOR WATERSHEDS LESS THAN
300 SQUARE MILES IN INDIANA.

FIG. 12


1.0
0
1.0
Relative Height $\frac{h}{H'}$
Relative Area $\frac{a}{A}$
α' = 0.40 .45 0.49 0.59 0.67 0.77
$\alpha' = \int_0^1 \frac{a}{A} \, d\left(\frac{h}{H'}\right)$

WU & DELLEUR
FIG. 14




n = 100 75 50 10
100,000
10,000
1,000
1000
10,000
n YEAR PEAK DISCHARGE Q_n (cfs)
25 YEAR PEAK DISCHARGE Q_{25} (cfs)